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ATTITUDE CNTL

ONE-AXIS RADIO ATTITUDE SENSOR

by

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ABSTRACT

A one-axis attitude sensor is described which may be used for specific attitude control systems on missiles, satellites or spacecraft. Its output signal is derived from on-board detection of the polarization of radio signals transmitted by a groundstation on earth. The sensitive axis is parallel to the line connecting groundstation and vehicle.

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SECTION I. INTRODUCTION

Although the function of the RF attitude sensor will be described using the example of a 24-hour satellite, this does not exclude other applications (e.g., attitude stabilization of missiles or spacecraft).

Figure 1 defines the reference system for the attitude control of a geostationary satellite. If this satellite is to be used for communication purposes, at least pitch- and roll-axis must be permanently controlled. Additional control (or programming) about the yaw-axis will usually be necessary for:

1. Antenna pointing (if the antenna pattern is not symmetrical about the yaw-axis)
2. Orientation of solar cells (or other solar power sources)
3. Thrust pointing during orbital correction maneuvers.

Considering the present state of the art (as well as the most likely development within the near future), it appears that pitch- and roll-sensing can be performed best by an optical or IR sensor. Such devices are rugged, lightweight, and have already proven their reliability.

In principle, yaw-sensing could also be done by an optical sensor, for instance by a Polaris seeker. Star seekers, however, are relatively complex and sensitive instruments. Furthermore, their acquisition field is very small, calling for search modes or other provisions to initiate lock on the target. It appears that the yaw-sensing function can be performed more economically and reliably by radio means. In the following, a simple one-axis RF sensor is described.

SECTION II. THE BASIC CONCEPT

The working principle of the RF attitude sensor is as follows:

A groundstation on earth transmits a linearly polarized radio signal. On the satellite this signal is received also by a linearly polarized antenna. The amplitude of the received signal is a function of the angular orientation of the receiver antenna relative to the transmitter antenna and can be evaluated as yaw-signal.

The implementation of this simple concept is connected with two major problems:

1. The polarization plane of radio signals is rotated between transmitter and receiver due to the Faraday effect. This rotation depends on the electron density of the ionosphere and therefore fluctuates in a random manner.

2. The evaluation of the signal amplitude as a measure of antenna orientation must be highly accurate and stable despite severe environmental conditions.

The first difficulty can be circumvented by chosing a sufficiently high signal frequency, for the Faraday rotation is proportioned to $1/f^2$, with f being the signal frequency. (E.g., for a frequency of 1 kmc the unpredictable portion of the Faraday rotation is expected to be less than 1 degree.)

The second problem - to achieve high sensitivity and stability - can be solved by (1) a particular operation mode of the transmitter providing time-shared transmission of two orthogonally polarized signals and (2) a bridge-like comparator circuit in the receiver.

Figure 2 shows the simplified block-diagram of the transmitter. The antenna switch (S) is driven by the low-frequency oscillator (0) and connects alternately the transmitter output with two antennas having polarization planes perpendicular to each other. Thus, two electromagnetic waves (the E-vectors E_1 and E_2 are indicated in Figure 3a) are generated according to the time functions represented in Figure 3b (the period T is $1/f_1$, f_1 being the frequency of oscillator 0).

The on-board device compares the signal amplitudes produced on a single receiving antenna with linear polarization by each of the orthogonally polarized waves. It is easily seen that both amplitudes are equal if the polarization of the receiver antenna lies in a plane 45 degrees to both polarization planes of the transmitted signals. (This case is indicated in Figure 3a; vector R symbolizes the polarization of the receiver antenna.)

In block-diagram Figure 4, the minimum on-board circuitry is accented by heavy lines. With mixer (M_1) and local oscillator (LO), the received signals are converted to a frequency convenient for amplification by the IF-amplifier (IF). Then follows a peak-detector (PD) and a bandpass filter tuned to the switch frequency $f_1 = 1/T$.

Figure 5 shows the output of the peak-detector as a time-function, depending on the orientation of the receiver antenna (R) with respect to the reference direction. An ac-voltmeter connected at point A, Figure 4, would measure the amplitude of the fundamental (frequency f_1) as an error signal, thus yielding the characteristic of Figure 6a (linear diagram) or 6b (polar diagram). It is seen that the zeros define the reference direction with an ambiguity period of 90 degrees. With this characteristic, the RF attitude sensor is not yet usable for a closed loop attitude control system, because the error signal indicates only the magnitude and not the sign of the angular deviation.

However, with a few additions to the primary circuit, it is possible to also distinguish the sense of angular deviations. The basic function of the additional components (light lines in Figures 2 and 4) is to identify the transmitted wave which generates the instantaneous signal amplitude. This is done with the aid of a reference (or timing) signal transmitted from the groundstation to the receiver. The extended circuit suggested in Figure 4 makes use of the fact that the ac-component of the peak-detector output is reversed in polarity if the receiver antenna passes the reference direction (see Figures 5a, b and c). Vectorial (i.e., phase sensitive) measurement of the fundamental will therefore result in a sensor characteristic as shown in Figure 7.

For the realization of the phase sensitive measurement, the switching frequency f_1 is directly used as a reference signal. f_1 is transmitted from the groundstation to the receiver by means of frequency or phase modulation (modulator "mod" in Figure 2, demodulator "D" in Figure 4). The demodulator output is filtered (bandpass BP_2 in Figure 4) and connected to a second mixer (M_2 in Figure 4). This mixer multiplies the reference voltage (frequency f_1) with the ac-fundamental of the peak-detector output (also frequency f_1). If the phase difference between the two sinusoidal voltages is zero, a positive (dc) error signal results; if the phase difference is 180 degrees, the error signal is negative. The low-pass filter (LP in Figure 4) is inserted to suppress the component of the frequency $2f_1$ which is also generated in mixer M_2.

The resulting diagram of Figure 7 still exhibits 4 zeros within 360 degrees. For any closed-loop attitude control system, however, only two "stable zeros" exist and the effective ambiguity is reduced to ± 180 degrees.

If the sensor is not operated within a closed-loop system, the "unstable zeros" of Figure 7 can be recognized and eliminated by introduction of a particular "quadrant signal". This auxiliary signal is generated by the components inserted with broken lines in block-diagram Figure 4 (45 degree phase shifter α and mixer M_3). The characteristic of the "quadrant signal" corresponds to that of the error signal but is rotated 45 degrees in a counter-clockwise direction. (Figure 8.)

In practice, the remaining ambiguity of plus or minus 180 degrees is not very disturbing. In many cases, it will be eliminated by knowledge of the direction to the sun (criterion: solar power on-off, or crude sun seeker). In other cases, a 180 degree ambiguity will even be appreciated, for instance if the satellite is to be reversed every 12 hours by a 180 degree rotation around the yaw-axis.

So far it has been assumed that the groundstation is located exactly at the satellite subpoint (Figure 2a). For any other transmitter location there is an angle (α in Figure 9) between yaw-axis and radio path. If the polarization of the two ground antennas is kept in a plane perpendicular to the yaw-axis, all previous considerations derived from the geometry of Figures 3a and 5, are fully applicable for any angle $\alpha < 90$ degrees.

Assuming, however, that the polarization is kept perpendicular to the (tilted) radio path, the angle α will also appear between the radio path and the rotation plane of the receiver antenna. Then, the reference (or "zero") direction of the yaw-sensor is defined by the intersection of the reference plane (45 degrees to both polarization planes of the transmitter antennas) with the local horizontal plane at the satellite. For any angle $\alpha \neq 0$, cross-coupling will occur between pitch-, roll-, and yaw-axis. However, since α is smaller than 8.5 degrees for any groundstation location (see Figure 9), this cross-coupling will be negligible.

SECTION III. DESIGN CONSIDERATIONS

Existing or off-the-shelf components can be used to a large extent for the transmitter and the transmitter antenna. Also, design of a fully transistorized receiver lies well within the state-of-the-art.

Since high transmitter power, high ground antenna gain and at least moderate gain of the on-board antenna are practicable, there is no need for an extremely sensitive receiver. For this reason, the receiver design can be aimed to achieve utmost simplicity and reliability.

The angular sensitivity of the attitude sensor is only a function of the overall amplification between antenna and mixer M_2 (including low-frequency amplification) and not subject to any practical limitation.

The accuracy of the angular measurement is mainly limited by the receiver noise. The effective noise bandwidth, however, is determined by the bandwidth of the filters BP_1 and BP_2 and can be made extremely narrow.

Since both signals (derived from the two orthogonally polarized waves) are propagated and processed in the same manner and through the same channel, changes in transmitter power, radio path attenuation or signal amplification may affect the amplitude of the error signal, but never the angular position of the "zero" (i.e., reference direction). Angular bias errors can only be caused by Faraday rotation of the RF signals and by mechanical misalignment of all three antennas. It is estimated that the sum of all (unpredictable) errors can be kept well below one degree.

Figure 4 shows only a simplified block-diagram of the receiver. The basic concept of the polarization-detection, however, remains unchanged if refinements, such as double conversion, phase-lock techniques, etc., are applied. "S" in block-diagram 2 can be a mechanical or an electronic switch.

The necessary output power of the ground transmitter is calculated by using a typical example:

Assumptions:	Signal frequency	2 kmc
	Distance	25000 mi
	Ground antenna gain	30 db
	Satellite antenna gain	13 db
	Receiver NF	10 db
	Receiver effective bandwidth	20 cps
	S/N ratio (in 20 cps band)	40 db
	Safety margin	3 db

$$\text{FKTB} = 10 \times 1.38 \times 10^{-23} \times 290 \times 20$$

$$= 0.8 \times 10^{-18} \text{ W} = -151 \text{ dbm}$$

Transmitter power = 39 dbm = 8 watt.

APPROVAL

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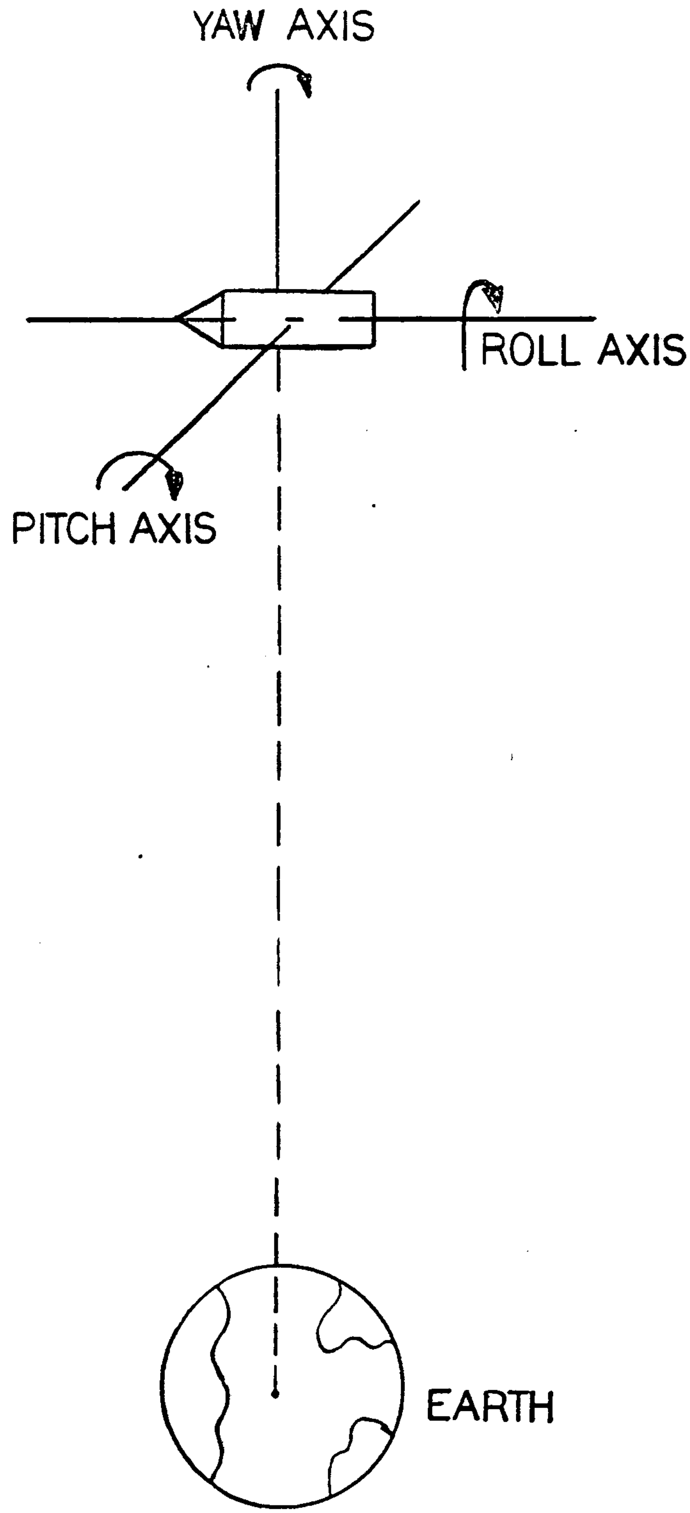
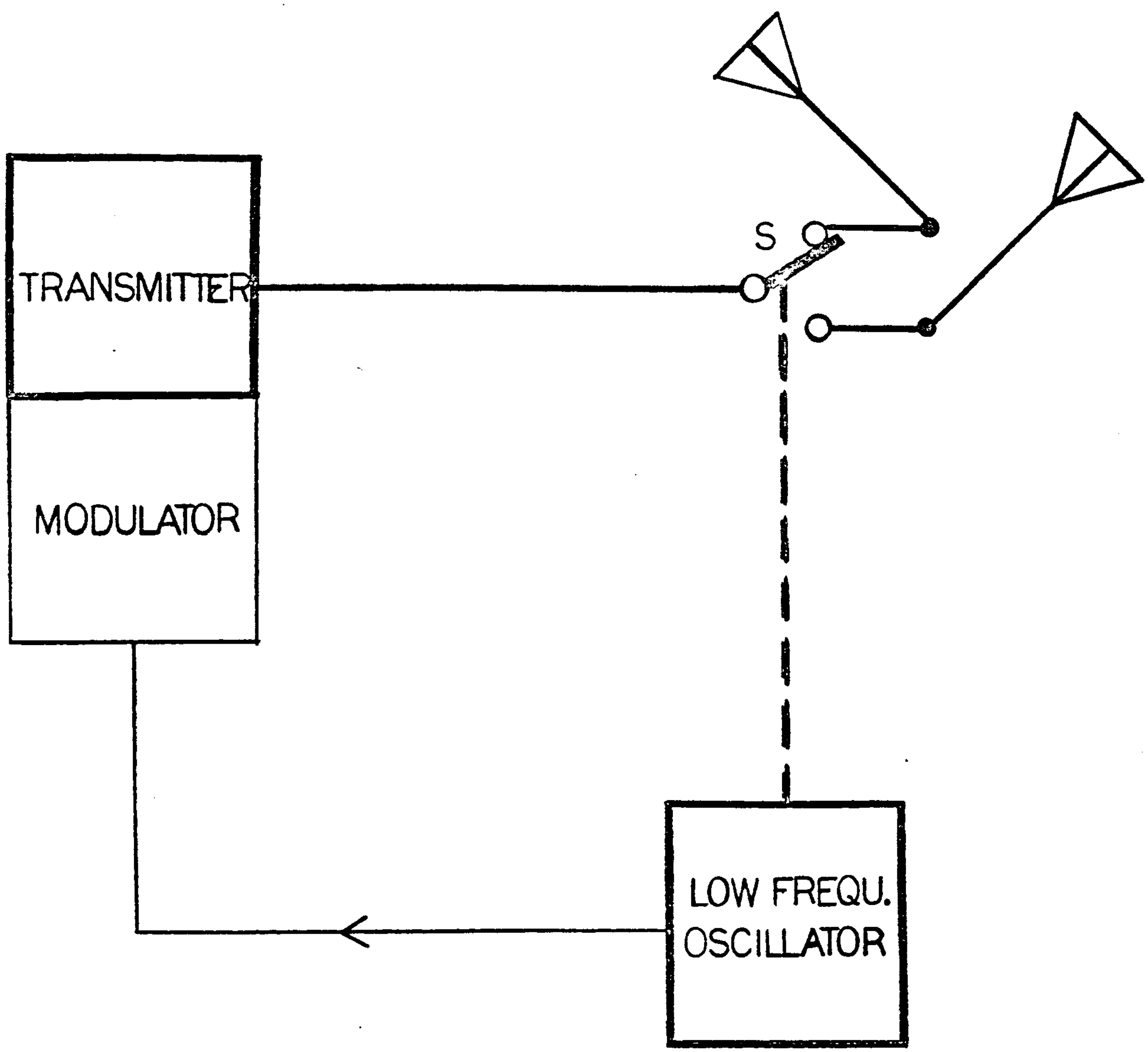


Reference System

FIG. I



Transmitter Block Diagram

FIG. 2

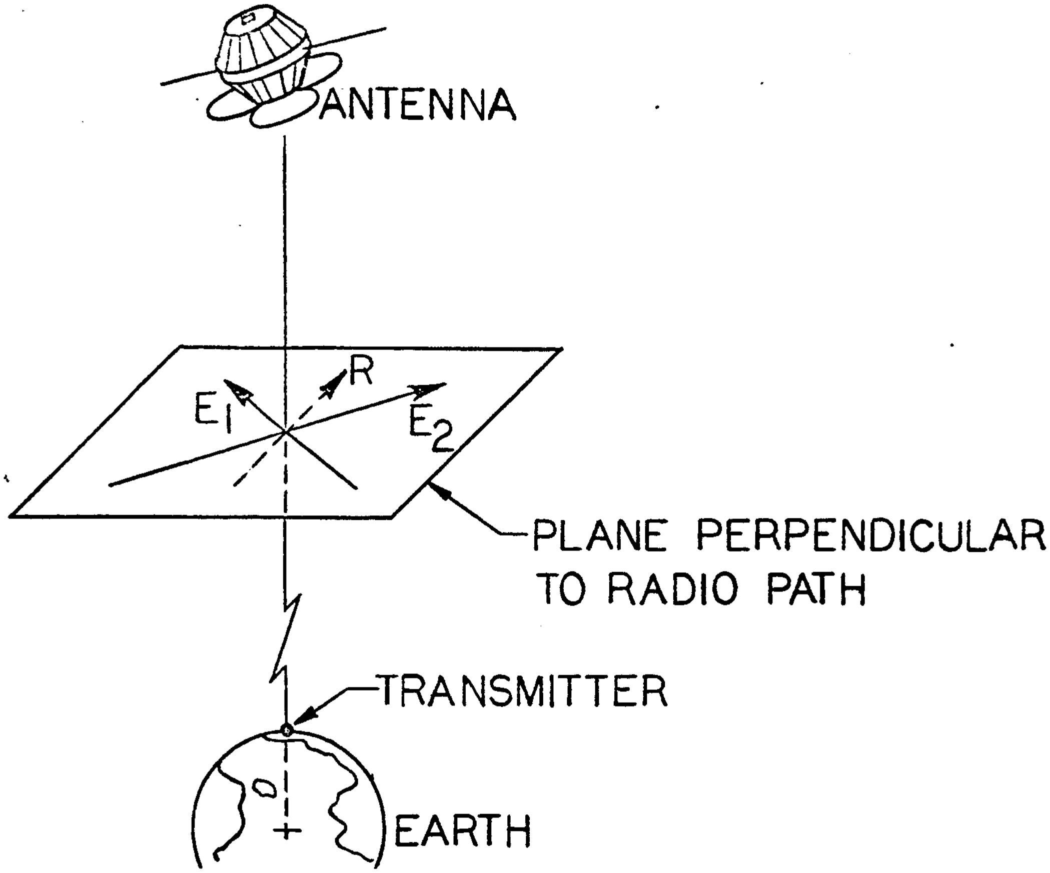


Fig. 3A. Polarization of the Radio Signals

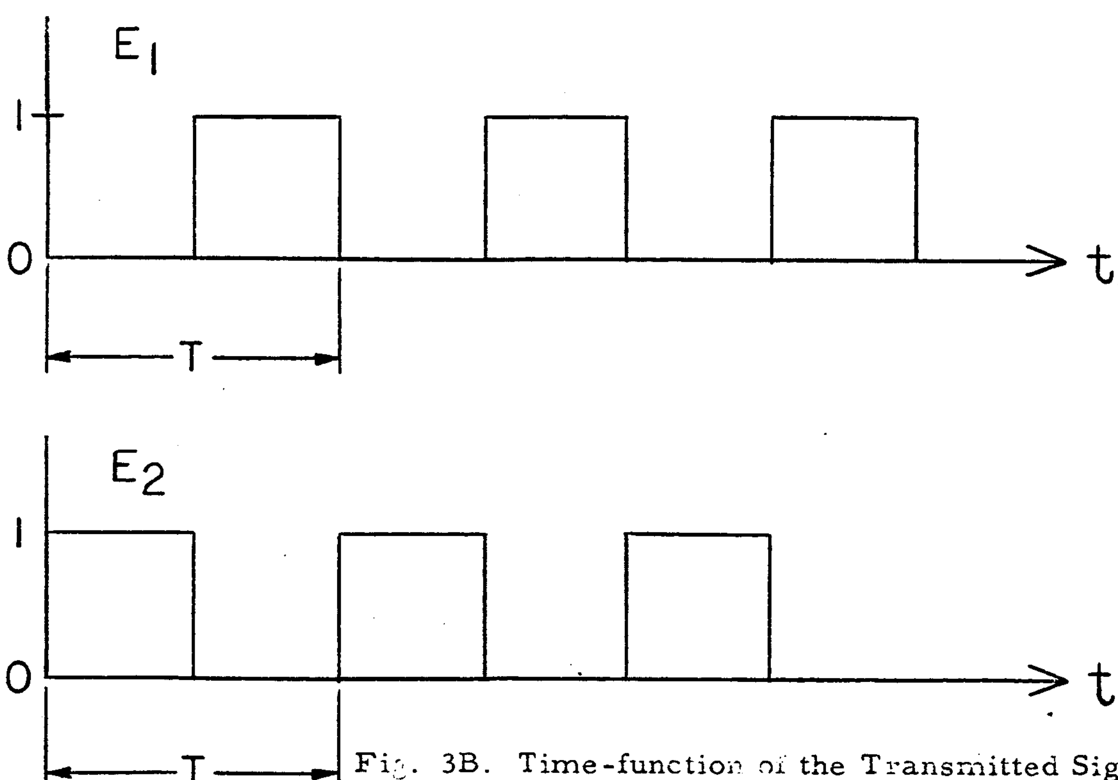
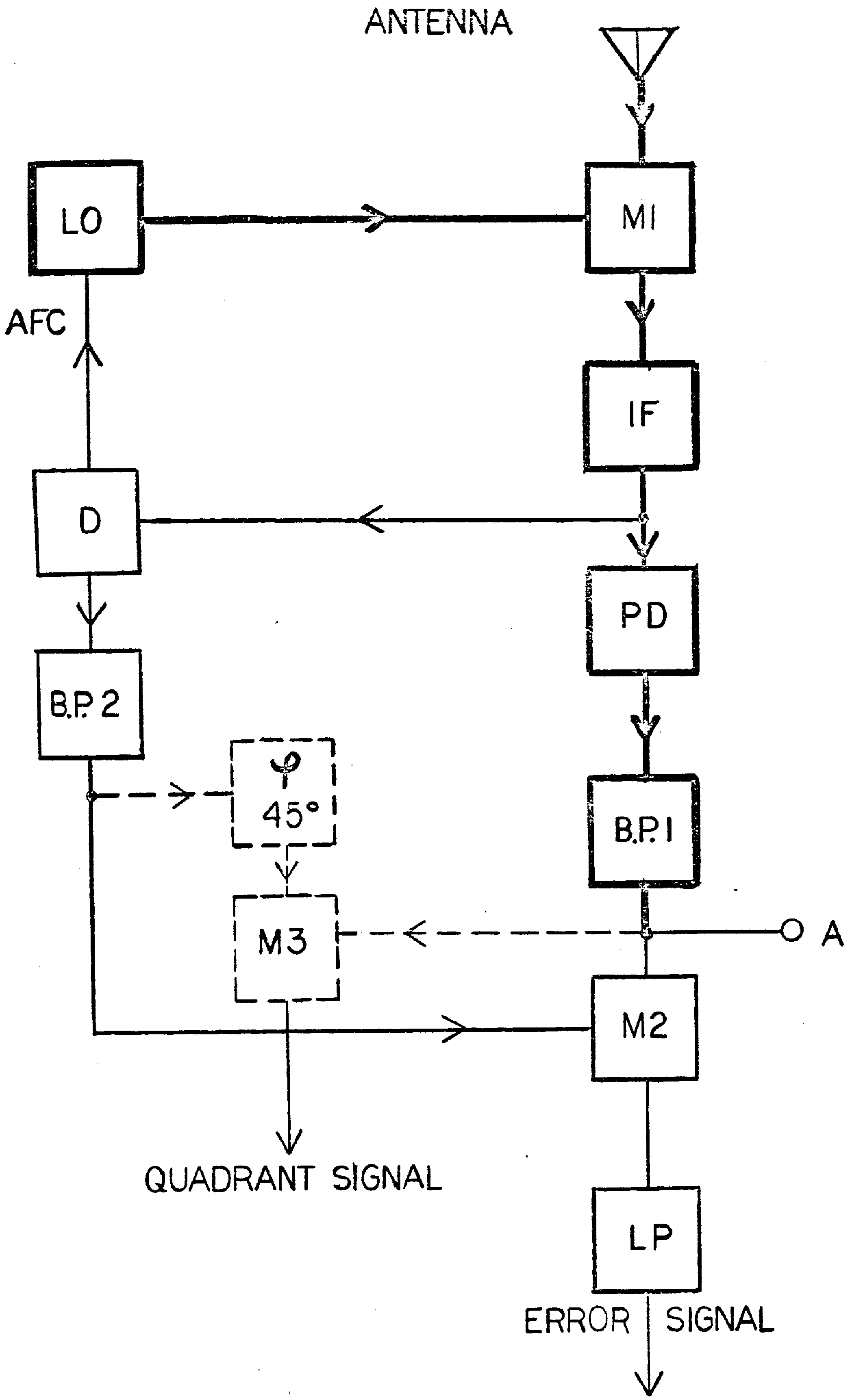
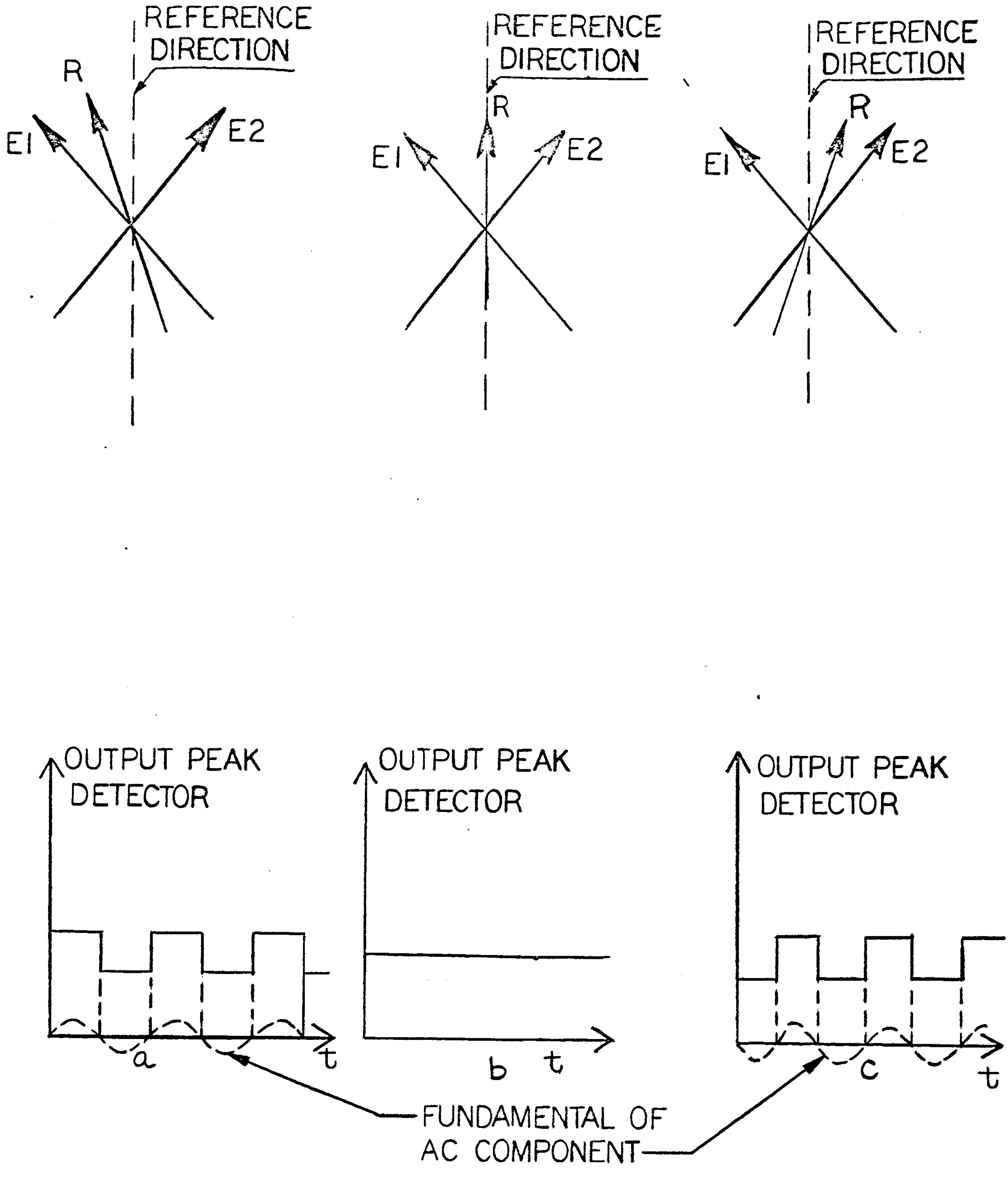


Fig. 3B. Time-function of the Transmitted Signals



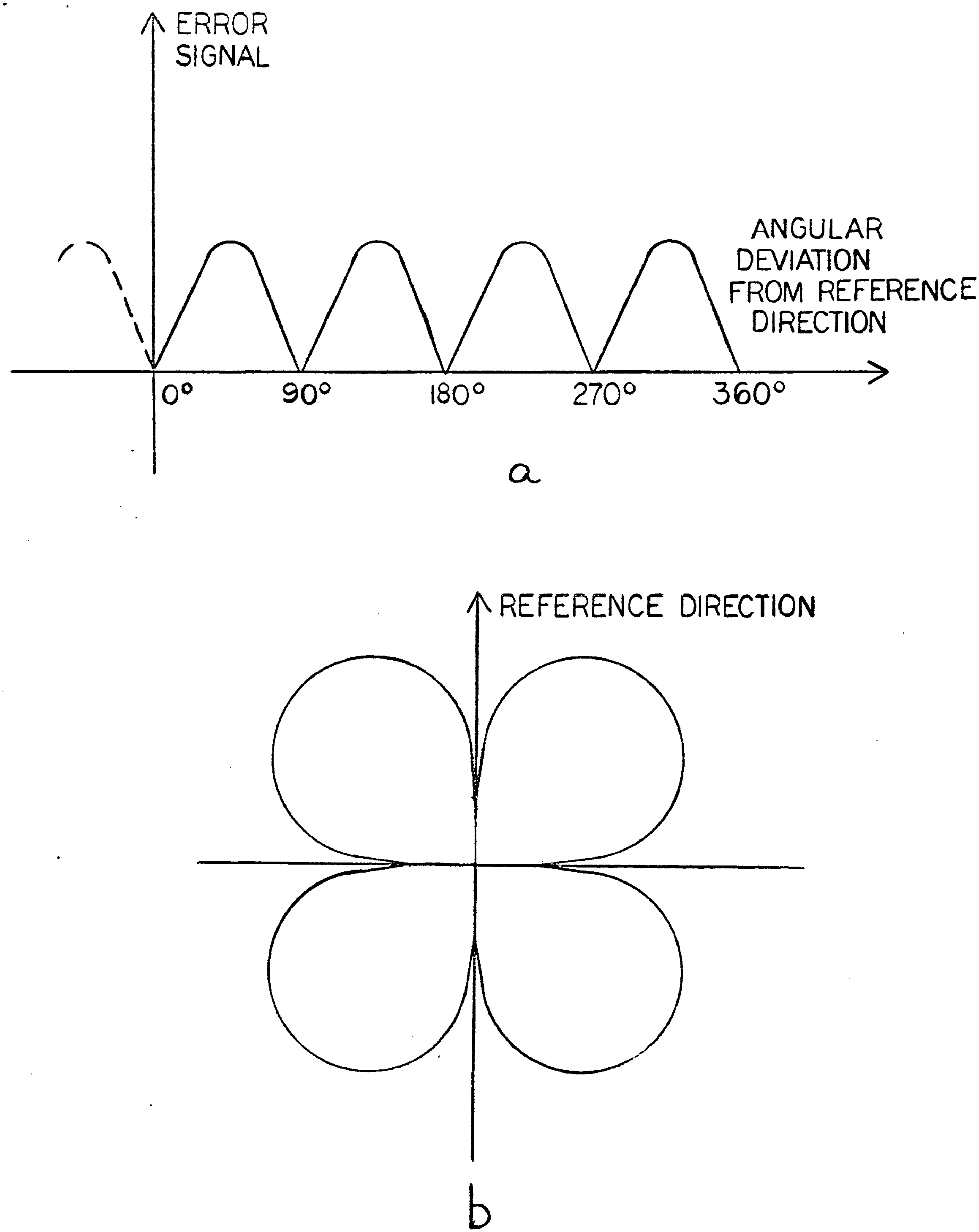
Receiver Block Diagram

FIG 4



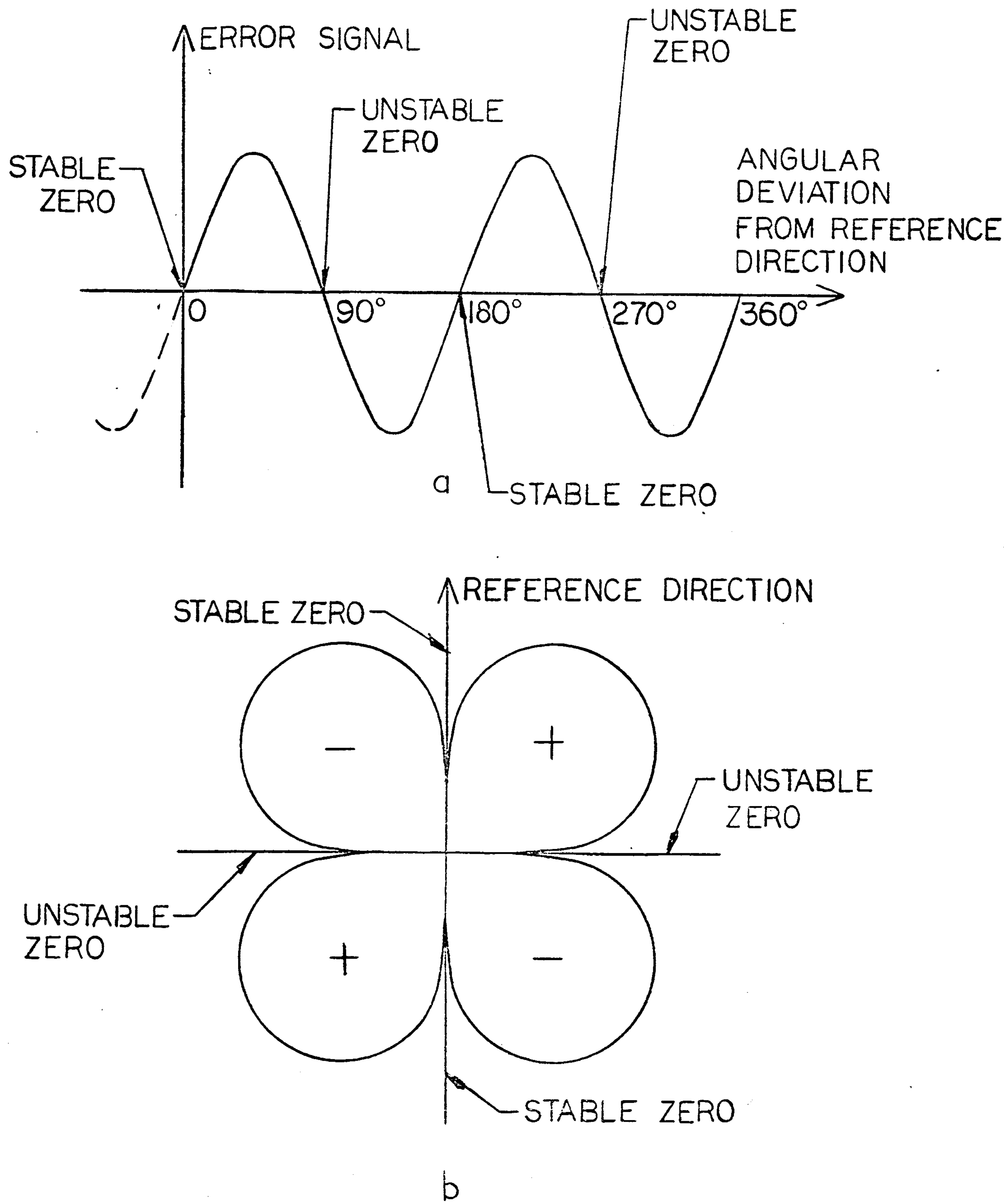
Time-function of the received signals

FIG. 5



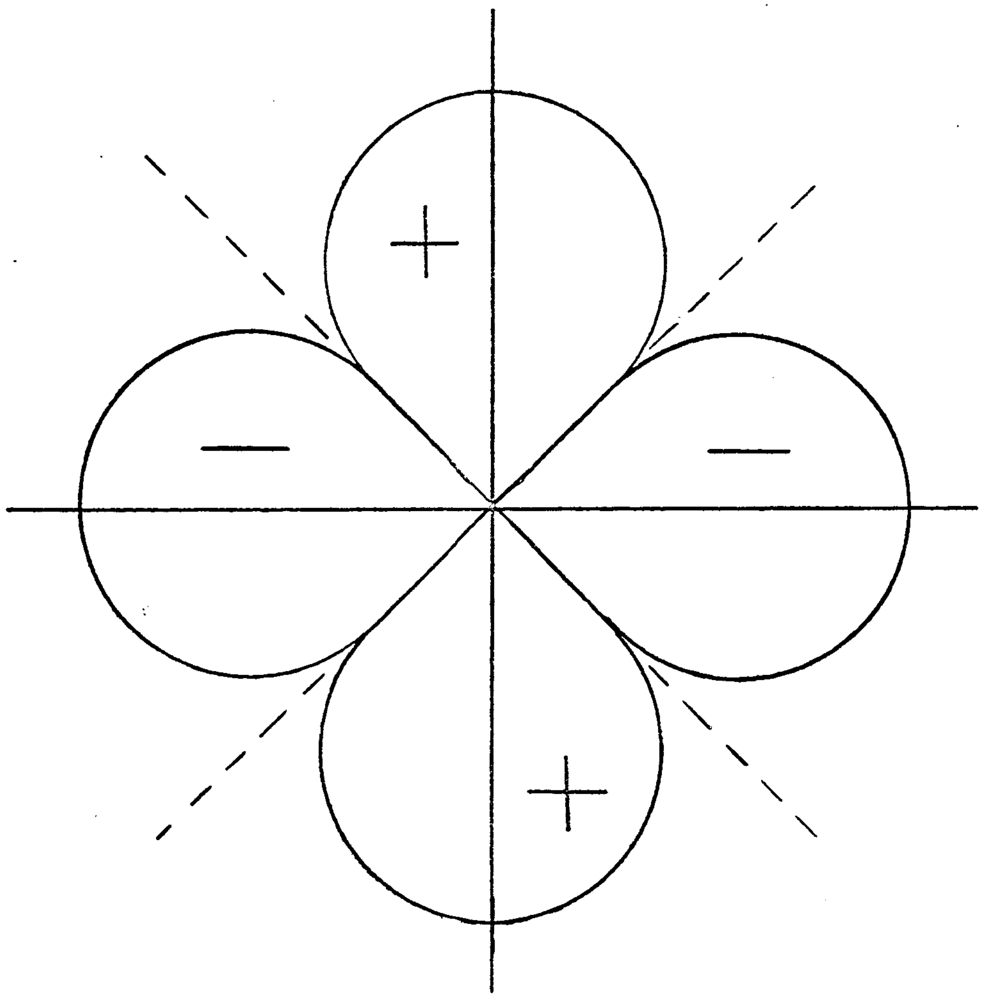
Error Signal Diagram for Peak-Detection

FIG. 6



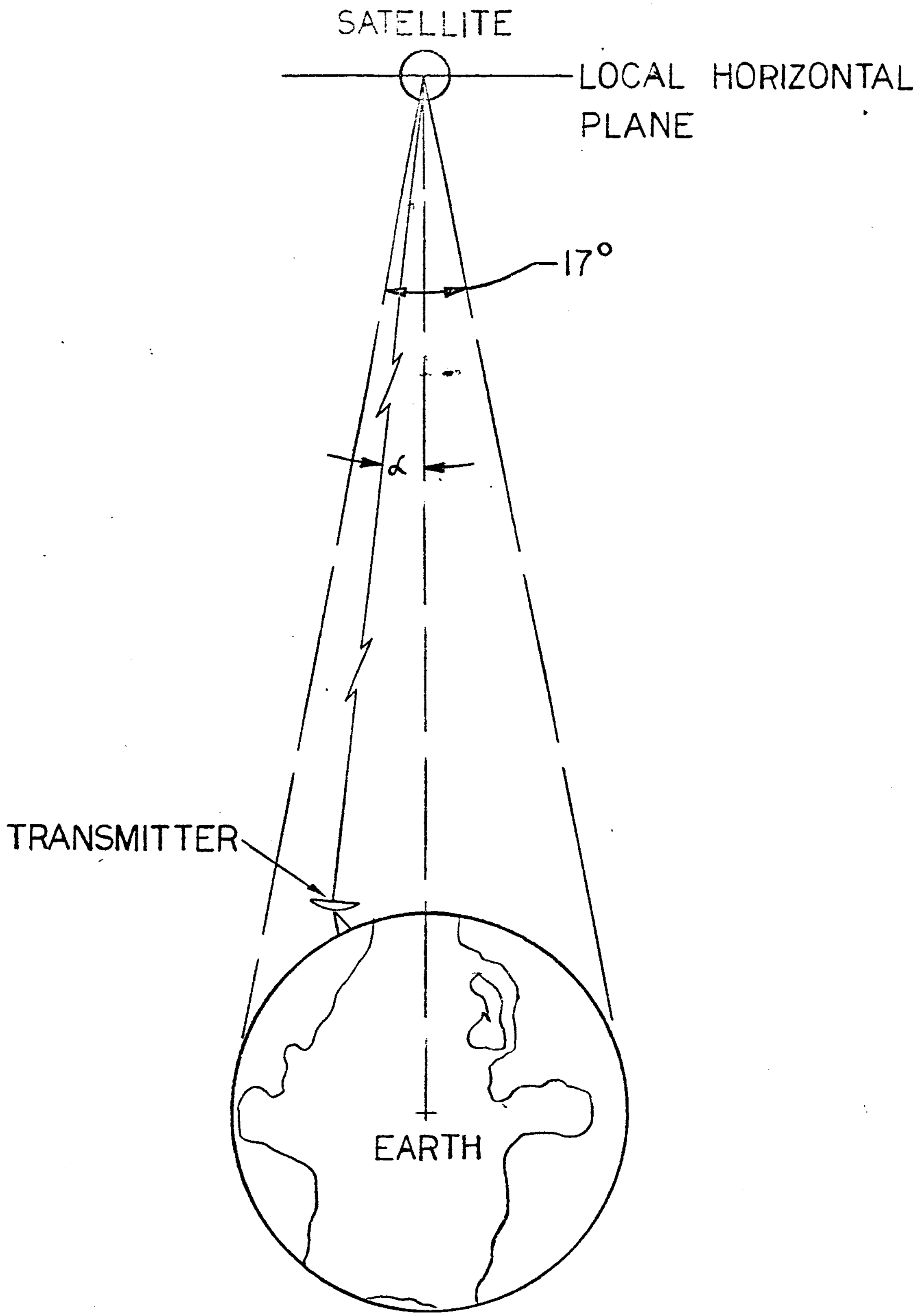
Error Signal Diagram for Phase Sensitive Detection

FIG 7



Quadrant Signal Diagram

FIG. 8



Location of Ground Station

FIG. 9